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Cooling techniques for improved productivity in turning

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ABSTRACT

The past century has witnessed significant advancements in turning process, cutting tools, machine controls and coolant/lubricant chemistry. These developments have particularly enhanced the machining of difficult-to-cut materials, which are used for aerospace, steam turbine, bearing industry, nuclear and automotive applications. In turning operation, friction and heat generation at the cutting zone are the frequent problems, which affect the tool life and surface finish apart from other machining results. This mechanism of heat generation plays quite a negative role during the turning of modern materials due to their peculiar characteristics such as poor thermal conductivity, high strength at elevated temperature, resistance to wear and chemical degradation. A good understanding of the methods of lubrication/cooling at the cutting zone, reduction of heat generation will lead to efficient and economic machining of these modern materials. This paper presents an overview of major advances in techniques as minimum quantity lubrication (MQL)/near dry machining (NDM), high pressure coolant (HPC), cryogenic cooling, compressed air cooling and use of solid lubricants/coolants. These techniques have resulted in reduction in friction and heat at the cutting zone, hence improved productivity of the process. A brief survey of modeling/FEA techniques is also performed.

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1. Introduction

Machining is the most widespread metal shaping process in mechanical manufacturing industry. All over the world, machining operations such as turning, milling, boring, drilling and shaping consume large amount of money annually [1]. Out of

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these machining processes, turning still remains the most important operation used to shape metals because in turning, the conditions of operation are most varied. Increasing productivity and reducing manufacturing cost have always been keys to successful business [2]. In turning, higher values of cutting parameters offer opportunities for increasing productivity but it also involves a greater risk of deterioration in surface quality and tool life [1,3]. Deterioration of surface quality during turning is directly related to the tool wear progression. Researchers have focused their attention on improvements in conventional turning, so that tool life can be enhanced or tool failure can be avoided. By tool failure is meant damage so large that the tool has no ability to remove material from workpiece. This tool damage cannot be avoided but we can find out ways to minimize it by analyzing its causes [4]. Stress and the temperature at the tool surface influence the damage at the cutting tool [5]. Tool damage is very sensitive to changes in the cutting conditions (cutting speed, feed rate and depth of cut) and presence of cutting fluid. While tool damage cannot be avoided, it can often be reduced if its failure mechanism and the factors controlling it are properly understood [1]. Tool damage is classified as: adhesion, thermal damage (plastic deformation, thermal diffusion and chemical reaction), mechanical damage (abrasion, chipping, fracture and fatigue). Out of these damages, thermal damage increases drastically with increasing temperature. Adhesion wear is also a temperature dependent phenomenon. The temperatures at which thermal damage and adhesion damage occur vary with tool and work material combination. Thus heat generation in turning leads to reduction in tool life and as a result reduced surface finish [4]. The diffusion type thermal damage occurs at high cutting temperature if cutting tool and work material elements diffuse mutually into each other's structure. The plastic deformation type of thermal damage is observed when a cutting tool at high cutting temperature cannot withstand the compressive stress on its cutting edge [2,6]. In metal turning operation, material is subjected to extremely high strain, and the elastic deformation forms a very small proportion of the total deformation; therefore, it may be assumed that all the energy is converted into heat [7].

As indicated in Fig. 1, conversion of energy into heat occurs in these principal regions of plastic deformation [8]. During the turning of metal, high temperatures are generated in the region of the tool cutting edge, and these temperatures have a controlling influence on the wear rate of the cutting tool and on the friction between the chip and the tool. The maximum temperature occurs along the tool face at some distance from the cutting edge [4]. The tool acts as a heat sink into which the heat flows from the flow zone and a stable temperature gradient is built within the tool. The amount of heat lost from the flow zone into the tool depends on the thermal conductivity of the tool, tool shape and the cooling method used to lower its temperature [2]. The heat generated

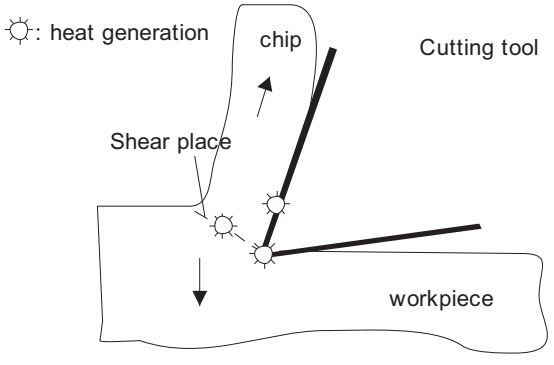


Fig. 1. Generation of heat in orthogonal turning [8].

during a cutting operation is summation of plastic deformation involved in chip formation, the friction between tool and workpiece and between the tool and chip [9]. Much of this heat remains in the chip, but a portion is conducted into the tool and the workpiece [10]. Laboratory tests have shown that reducing cutting temperature is important since a small reduction in temperature will greatly increase cutting tool life [11]. In the absence of cutting fluid, the heat carried away from the cutting zone is decreased, resulting in an increase in tool and workpiece temperature [12]. The cost of machining is very strongly dependent on metal removal rate (MRR), but increase in MRR leads to shortening of tool life due to increase in friction and heat generation at the tool cutting zone. Many of the economic and technical problems of machining are caused directly or indirectly by this heating action [2]. That heat plays a part in machining was clearly recognized by Taylor in 1907 [13]. The limitation imposed by cutting temperatures has been spur to the tool materials development in the past century. It is, therefore, important to understand the factors, which influence the generation of heat, the flow of heat, and the temperature distribution in the tool and work material near the cutting edge [2,4]. High cutting temperatures in machining always result in aggressive adhesion wear at the tool surface [14]. Conventionally, cutting fluid is used to cool and lubricate the cutting process, thereby reducing tool wear and increasing tool life [15]. The cost of cutting fluids is approximately 7%–17% of the total cost in machining process [16]. As cutting fluid is applied during machining operation, it removes heat by carrying it away from the cutting tool/workpiece interface [17]. This cooling effect prevents the tool from exceeding its critical temperature range beyond which the tool softens and wears rapidly [18]. Several technologies have been developed in recent years for controlling the temperature in the cutting zone in order to increase the overall effectiveness of the process like cryogenic cooling, solid coolants/lubricants, flood cooling, minimum quantity lubrication (MQL)/near dry machining (NDM), high pressure coolants (HPC), internal tool cooling and use of compressed air/gases as shown in Fig. 2.

The above approaches have been tested by the researchers in the past for their ability to keep process temperature low in order to reduce the tool wear. Traditionally high temperature in cutting zone has been controlled by using cutting fluid. The cutting fluid helps to improve the surface finish as well as to facilitate chip flushing [19]. It performs both coolant and lubricant function simultaneously. The coolant effect reduces the temperature in cutting zone and the lubrication action decreases cutting forces. Thus the friction coefficient between the tool and chip becomes lower in comparison to dry machining [20]. Minimizing the friction between the cutting edge of the tool and workpiece, corrosion control, chip ejection and washing are the functions of the cutting fluid in machining [21]. Researchers have focused their attention on issues related to environmental problems, fluid disposal, toxicity, filterability, misting, staining, surface cleanliness and indirect cost involved while using coolant/lubricants and have tried to find out ways to improve the current techniques of cooling during turning in order to reduce the temperature at the cutting zone and to eliminate/minimize these problems. The lubricating action is more important at low cutting speed, whereas the cooling effect is more important at higher cutting speed due to large increase in heat generated by the chip removal process [2].

2. Cutting mechanics with cryogenic cooling

In cryogenic cooling, the liquid nitrogen (LN) at −196 °C is applied to the cutting zone for reduction in cutting temperature

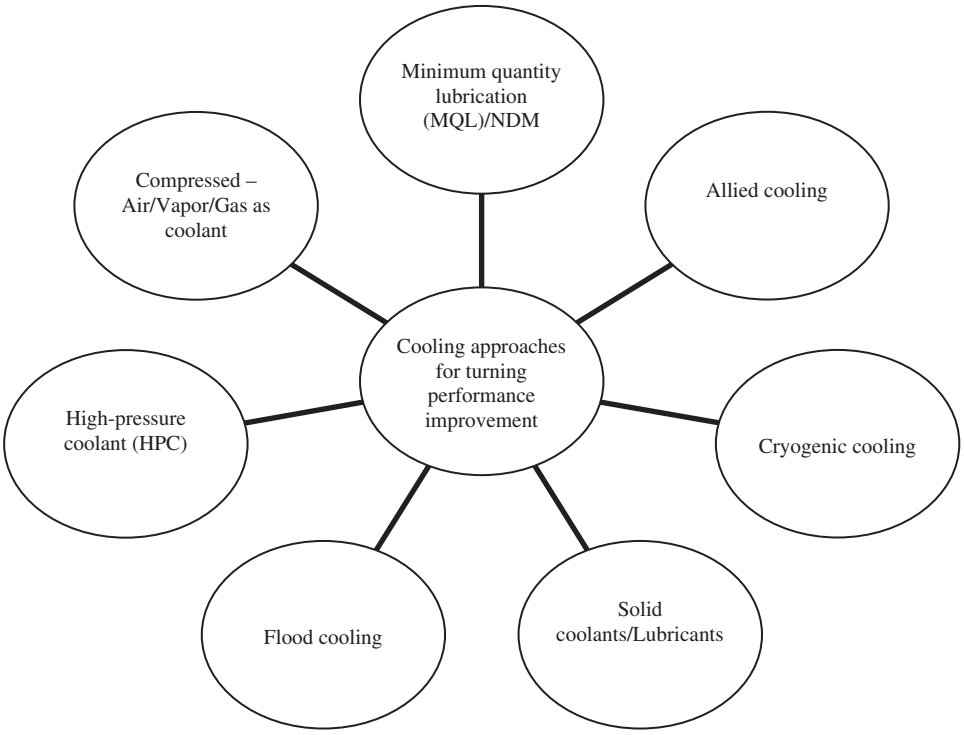
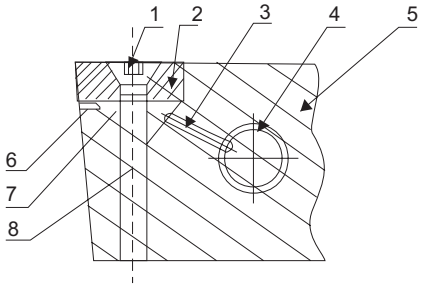


Fig. 2. Techniques for reduction in heat generation during turning.

[22]. The flow of nitrogen is carefully delivered to the point where it is needed [23]. As nitrogen evaporates harmlessly into the air, there is no cutting fluid to dispose. Chips generated from this technique have no residual oil on them and can be recycled as scarp metal [24]. Improved machinability with cryogenic cooling is attributed to a reduced diffusion-related wear mechanism and less degraded tool hardness or a reduced yielding strength at lower temperature [25]. The heat generation becomes more intensified in machining of hard materials because the machining process requires more energy than that in cutting a low strength material. Additionally, the thermal conductivity of the advanced materials such as silicon nitride (about 13 W/m °C), titanium alloy (about 15 W/m °C) and inconel (about 11 W/m °C) is much lower than that of commonly used alloy steels. As a result, the cutting temperature in the tool and the workpiece rises significantly during machining of these advanced materials. Thus the most practical and effective way to enhance the machining performance in cutting difficult-to-cut materials is to reduce the temperature generated during cutting [26].

Cryogenic cooling is the efficient way of maintaining the temperature well below the softening temperature of the cutting tool material [27]. Cryogenic cooling is an environmentally safe alternative to conventional emulsion cooling. In the past common cryogenic cooling approaches included pre-cooling the workpiece, indirect cooling, general flooding and enclosed bath [28]. The liquid nitrogen absorbs the heat, evaporates quickly, and forms a fluid gas cushion between the chip and the tool face that functions as a lubricant [29,30]. Reduction in tool temperature during cryogenic cooling is by lubrication and cooling the hottest spot that in turn reduces the carter and flank wear. Besides being environment friendly, cryogenic cooling, if properly employed, can provide, significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of cryogenic cooling system and cryogenic fluid [31,32]. Beneficial effect of cryogenic cooling by liquid nitrogen may be attributed to effective cooling, retention of



where (2) insert, (3) small hole passage, (4) liquid nitrogen entry point, (5) tool holder, (6) very small hole for gases nitrogen passage, (7) expanding chamber for liquid nitrogen, (8) threaded screw.

Fig. 3. Tool for cryogenic cooling [26].

tool hardness and favorable interactions of cryogenic fluid with chip–tool and work–tool interface [33]. Cryogenic cooling has been observed to have a favorable influence on chip breaking and reduction in cutting temperature during turning [34]. The benefit of cryogenic cooling has been more predominant at lower cutting velocity expectedly because at lower velocity a large portion of the chip–tool contact remains elastic in nature, which is likely to allow a more effective penetration of cryogen at the interface [27].

Specially designed tool holder was used in which liquid nitrogen was converted into gaseous state before coming in contact with the tool insert as shown in Fig. 3 and nitrogen was made to flow just beneath the insert through a small hole. During turning of stainless steel with coated carbide tools, tool life with a cutting speed of 100 m/min–300 m/min was plotted as shown in Fig. 4. Result shows that with conventional coolant the tool life was 13.45 min at 100 m/min speed and 0.5 mm depth of cut, whereas under same cutting conditions in cryogenic cooling, the tool life was 57.45 min. It shows that the application of cryogenic coolant has increased the tool life by 4.27 times [26]. During the

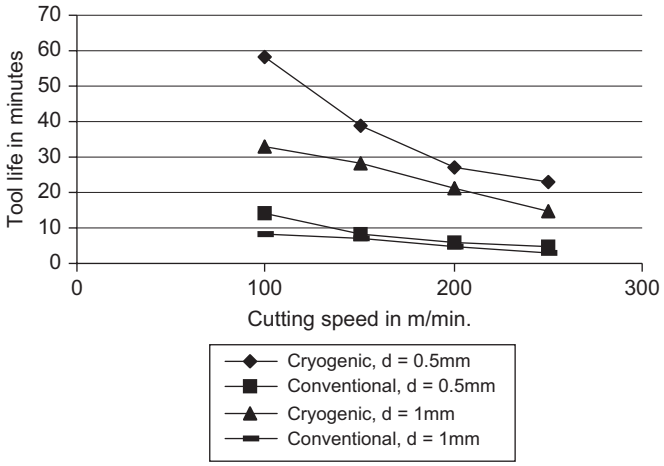


Fig. 4. Tool life at different cutting speed ($f = 0.1$ mm/rev) [26].

machining of Ti–6Al–4V alloy using uncoated micro-crystalline K20 tungsten carbide inserts at 70 m/min speed, 0.2 mm/rev feed and 2 mm depth of cut, with cryogenic cooling, maximum flank wear reduces 3.4 times as compared to dry turning and 2 times as compared to wet turning. Such reduction in wear is seemingly indebted to reduction of the temperature-sensitive wear phenomenon like diffusion and adhesion enabled by direct and indirect cooling with the liquid nitrogen jet. It was observed that such benefits decreased under high velocities of 100 and 117 m/min possibly due to improper penetration of liquid nitrogen in the chip–tool interface. Flaking of the rake surface just at the end of the crater wear region was observed especially under cryogenic machining condition. This is attributed to higher thermal gradient at the end of crater contact [29].

Performance of polycrystalline boron nitride (PCBN) tools under dry and cryogenic cooling conditions is studied during turning of reaction bonded silicon nitride (RBSN). The maximum temperature experienced with cryogenic cooling is only 829 °C as against 1153 °C in dry cutting. Special cup type arrangement of tool holder is used and there is little vaporization and no frozen ice blocking in the coolant circulation system, which frequently occurs with external spray method. Secondly, in this method liquid nitrogen does not directly come in contact with the workpiece. Therefore, it does not result in any extra size change or poor accuracy caused by serious temperature changes on the machined surface. There is an increase in roughness value by 16 μm with dry cutting as compared to cryogenic cooling; this variation in surface roughness is due to increase in tool wear under dry conditions [30,35]. Cutting force with cryogenic cutting is less than that with dry cutting. This is because application of cryogenic fluid reduces the coefficient of friction at the interface of the tool–chip over the rake face [36].

It is observed that during machining of steel rods (AISI 1040 and E4340C steel) with carbide inserts having grooves along the cutting edges and hills on the tool rake face as mentioned in Fig. 5, cryogenic cooling reduces the average cutting temperature, because the above said geometry helps the cryogenic jet to come closer to the chip–tool interface and thus effectively cool the interface [37]. Two different designs for cryogenic cooling with modified tool holder were proposed as shown in Fig. 6(a) and (b). In design I, the gas is directed towards the tool cutting edge, to cool the newly generated chips. This will enhance the chip brittleness for easy chip breaking. In design I, the fluid exit is made closer to the tip of the cutting tool. In design II, the fluid exit is made away from the tip of the cutting tool as a result the

Fig. 5. Carbide insert having grooves along the cutting edge [26].

discharging gas is directed away from the workpiece. This design is useful for those materials in which excessive cooling has a negative effect on their ductility. Analyzing Fig. 7, it can be noticed clearly that design II exhibited better wear resistance in comparison to design I. This is due to the fact that in the case of cryogenic tool design II, the workpiece is cooled by the nitrogen outflow, which discharges the evaporated gas away from the cutting edge and the chip. This maintains the workpiece ductility, while keeping the tool insert itself at a very low temperature and thus better wear resistance. This design is recommended for cutting materials that have strong temperature–ductility relations [31]. Cryogenic cooling expectedly reduced main flank and auxiliary flank wear because of the fact that the liquid nitrogen jet especially impinged along the auxiliary cutting edge. During the turning of AISI-4037 steel under cryogenic conditions, the liquid nitrogen jet has been used mainly to target the rake surface and flank surface along the auxiliary cutting edge [32].

During the turning of AISI 1060 steel by carbide inserts, cryogenic cooling with liquid nitrogen jet provided reduced tool wear, improved surface finish as compared to wet and dry machining. The use of liquid nitrogen in cryogenic cooling is beneficial due to effective cooling, retention of tool hardness and favorable chip–tool, work–tool interactions [33].

Result shows that cryogenic CO_2 applied at a rate of about 6 g/s is an efficient coolant for threading as well as for parting/grooving of stainless steel. The efficiency of CO_2 plus oil is 15% higher than that of the commercial water based product. In parting/grooving, the efficiency of CO_2 with addition of a highly chlorinated mineral oil was remarkably superior, up to 70% higher, than that using the water based product, suggesting that good results can be expected in parting/grooving after lubricant optimization under cryogenic conditions [38]. During the turning of hardened powder metallurgy particulate material, cryogenic nitrogen cooled Al_2O_3-based cutting tools were found to live significantly longer than the conventionally cooled CBN and resulted in less thermally affected surface of machined part [39].

Cryogenic cooling has been executed in cutting operations in different ways by using liquid nitrogen for pre-cooling the workpiece, cooling the chip, cooling the cutting tool and cutting zone. In comparison to dry cutting and conventional cooling, the most considerable characteristic of the cryogenic cooling application is control of machining temperature desirably at the cutting zone, thus reduction in tool wear and improved surface finish [40].

2.1. Performance of cryogenic cooling under different cutting regime

1. Optimization of the flow rate and application pressure of liquid nitrogen is important in order to get continuous flow of liquid nitrogen without over-cooling of the workpiece. If overcooling of the workpiece takes place, more cutting force is required. Further, it may lead to embrittlement of the work material. Also proper positioning of the nozzle is required to protect flank, rake and auxiliary flank face.

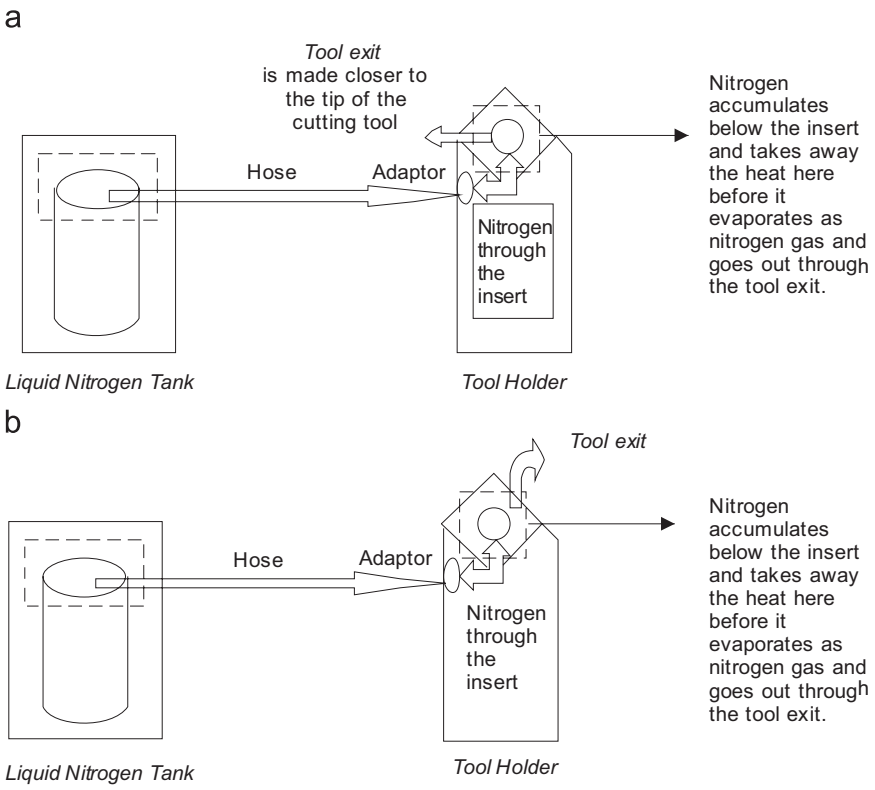


Fig. 6. Schematic sketch of cryogenic cooling (a) Design I (b) Design II [31].

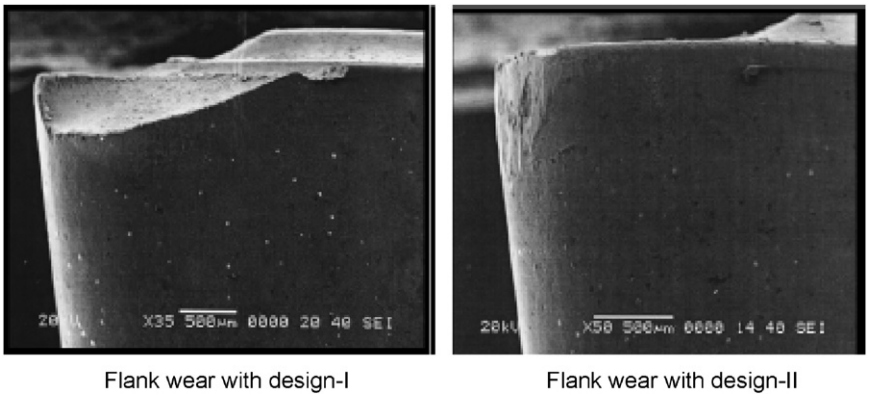


Fig. 7. Flank wear under different designs [31].

2. Cutting force in cryogenic turning is less than that in dry turning. This is because application of cryogenic fluid reduces the coefficient of friction at the interface of the tool and chip over the rake face.
3. Cryogenic cooling effect slightly decreases at higher cutting speed; this may be attributed to the fact that with the increase in cutting speed, the chip–tool contact tends to become fully plastic obstructing penetration of the cryogen into the hot chip–tool interface. Grooves along the cutting edge of the tool may be advantageous in high-speed cryogenic cutting.
4. At a higher feed rate chip thickness is higher; plastic deformation at the shear zone takes place at a faster rate generating more heat. Therefore, cryogenic cooling is more effective at a higher feed rate.
5. By selectively applying liquid nitrogen to the chip and tool rake face through well-controlled jet, tool life can be enhanced. Micro-temperature manipulation with cryogenic cooling is the best means of chip control in the machining of difficult-to-cut materials.
6. During turning with carbide tools under cryogenic cooling notching, abrasion, adhesion and diffusion type wear can be retarded effectively leading to remarkable improvement in tool life.

3. Analysis of minimum quantity lubrication/near dry machining

Minimal quantity lubrication/Near dry machining: In this, very small lubricant flow (ml/h instead of l/min) is used. The lubricant is mixed with air to form an aerosol and delivered close to the

cutting edge [41]. In MQL application, heat transfer is predominantly in the evaporative mode, which is more efficient than the convective heat transfer prevalent in conventional wet turning [42]. There are reports of attempt to introduce cutting fluid at the tool–chip interface through specially designed cutting tools, which brings forth better tool life [43], better surface finish [44], low cutting force and better chip forms [45]. It reduces machining floor space; eliminates coolant pump, coolant testing, coolant treatment and coolant disposal and allows the operator to observe the performance during machining [4].

Metal cutting fluids change the performance of machining operations because of their lubrication, cooling and chip flushing functions but the use of cutting fluid has become more problematic in terms of both employee health and environmental pollution [46]. The minimization of cutting fluid also leads to economic benefits by way of reducing lubricant costs and workpiece/tool/machine cleaning cycle time. Nearly a decade ago, the concept of minimum quantity lubrication was suggested as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors. Flooding of fluid lead to various drawbacks like increase in overall cost of cutting, problem of disposal of the fluid, etc. So MQL seems to be a good alternative for effective cooling during machining. [47].

The influence of oil mist on tool temperature in cutting is investigated. The tool temperature at 300 m/min is 1060 °C in dry cutting, but is 1000 °C when the oil mist is supplied. The difference of temperature of 60 °C is equivalent to a difference in cutting speed of 50 m/min. There is little effect on tool temperature in air blowing with no oil mist. The setting location of the nozzle is an important factor in the effective application of oil mist. In turning, the nozzle orientation of the horizontal angle $\psi = 45^\circ$ and the vertical angle $\theta = 45^\circ$ is most effective for the rake surface temperature [3].

In MQL, two different mixing methods can be used: mixing inside nozzle and mixing outside nozzle. Using the mixing inside nozzle equipment, pressurized air and lubricant are mixed into the nozzle by a mixing device, as shown in Fig. 8(a). Lubricant performs the lubrication action, while the pressurized air that reaches the cutting surface performs cooling action. This method has several advantages. Mist and dangerous vapors are reduced and the mixture setting is very easy to control. In the mixing outside nozzle method as shown in Fig. 8(b) the mixture is obtained in a mixing device positioned in a specific tank. In this method, lubrication between workpiece and tool can also be achieved [48].

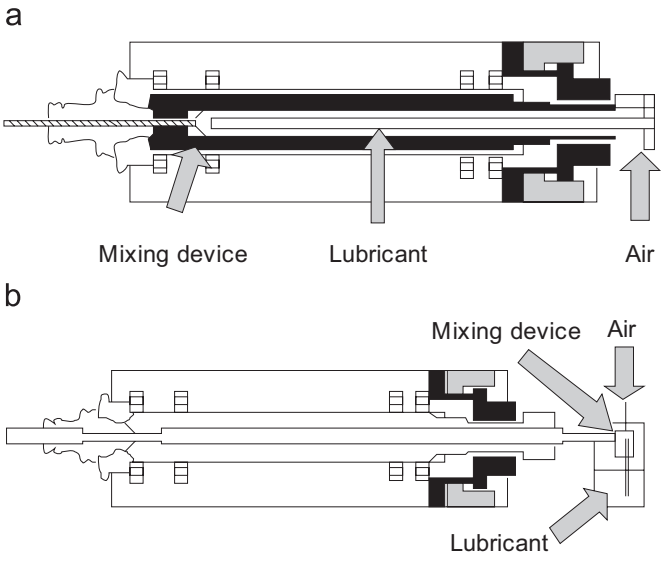


Fig. 8. Different methods of mixing lubricant in MQL [48].

A comparison of dry, rake MQL and flank MQL for surface finish and tool life was made as mentioned in Fig. 9(a) and 9(b). Under similar cutting conditions, removed volumes with flank MQL are equal to or greater than those in other conditions. For fixed cutting length a rise in feed rate always causes a reduction in tool life, but with flank MQL tool life lies consistently above the others. Also it is observed that dry cutting and rake face MQL generally have the same behavior. It is assumed that when MQL is applied on the rake surface, the lubricant does not reach the cutting surface. Further EDS microanalysis of inserts used in rake MQL conditions does not show presence of any chemical compound on the worn surfaces. This means that, when MQL is applied on the rake surface, lubricant does not reach the cutting area. Under this condition, it is impossible to reduce the tool wear. As far as the influence of cutting length is concerned, the mean tool life in flank MQL conditions increases with cut length, whereas in dry and rake MQL conditions, cutting length does not influence tool life. Traces of lubricant compounds have been found on the worn surfaces only when MQL has been applied on the flank surface.

In MQL machining, a small amount of vegetable oil or biodegradable synthetic ester is sprayed to the tool tip with compressed air. The consumption of oil in industrial applications is in a range of approximately 10–100 ml/h. MQL machining is nearly equal or often better than the traditional wet machining in terms of tool life. During the finish turning of Inconel 718 with coated carbide tools (with chip breakers) under MQL (biodegradable synthetic ester as lubricant), the cutting fluid was supplied to

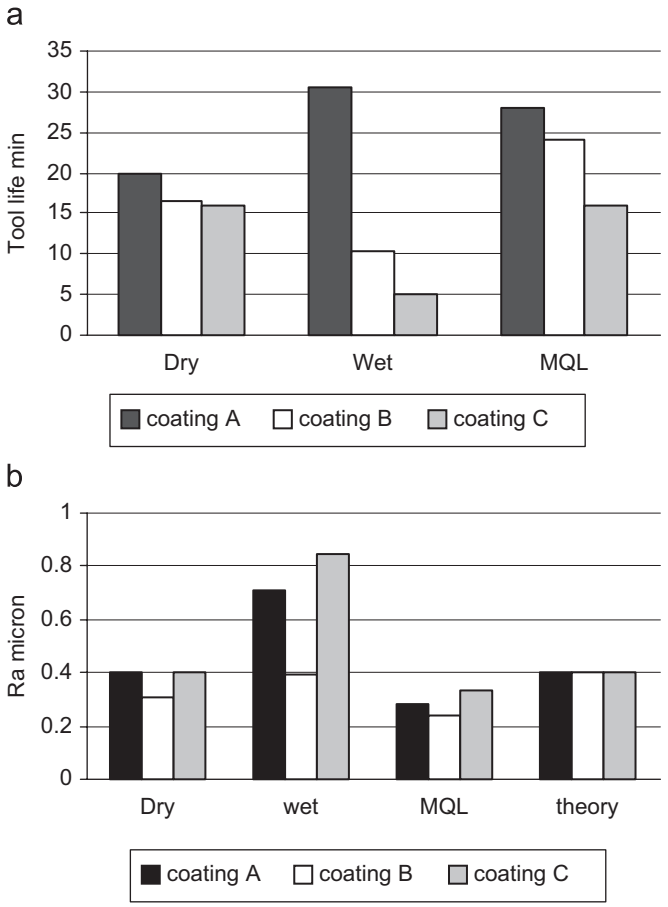


Fig. 9. Tool lives and surface finishes of the three coated tools in MQL, wet and dry cutting: (a) tool life and (b) surface finish at tool life [49].

Fig. 10. Oil holes in the tool holder for MQL [49].

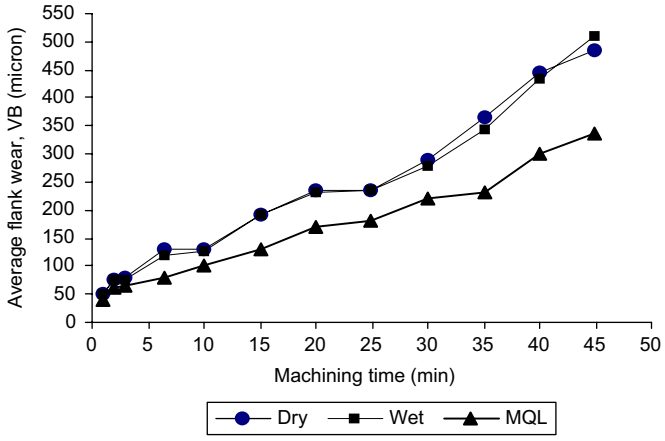


Fig. 11. Progression of average principal flank wear [50].

the cutting point with compressed air through oil holes on both the flank and rake faces of the tool as shown in Fig. 10. Comparative analysis of oxygen and argon as carrier gas reveals that poor heat capacity, poor thermal conductivity and poor lubrication characteristics of argon gas have increased cutting temperature and tool wear. Extending the quantity of lubricant can help in increasing the surface finish [49].

The MQL jet has been used mainly to target the rake and flank surfaces and to protect the auxiliary flank to enable better dimensional accuracy. As shown in Fig. 11 the rate of average principal flank wear is decreased by MQL, This is due to reduction in flank temperature by MQL, which helps in reducing abrasion wear by retaining tool hardness and also adhesion and diffusion types of wear which are highly sensitive to temperature. Also temperature control by MQL reduces the growth of notch and groove wear on the main cutting edge. Surface roughness during MQL reduces mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation [50].

During the turning of AISI 4340 alloy steel with coated (TiCN)/T1 and (ZrN)/T2 hard metal inserts by applying cutting fluid at pressure of 10 MPa and at 8 ml/min, flow rate variation of cutting force, surface roughness and cutting temperature were analyzed and further comparisons were made between wet, dry and minimum fluid application. It is observed that the cutting force is (as mentioned in Fig. 12) lower in minimal fluid application, as compared to dry and conventional wet turning for both the tools because of the fact that during minimal application of cutting fluid, the cutting fluid is fragmented into tiny globules with their size inversely proportional to the pressure of injection. The velocity varies as a function of the square root of the injection pressure. This high velocity facilitates better penetration of the

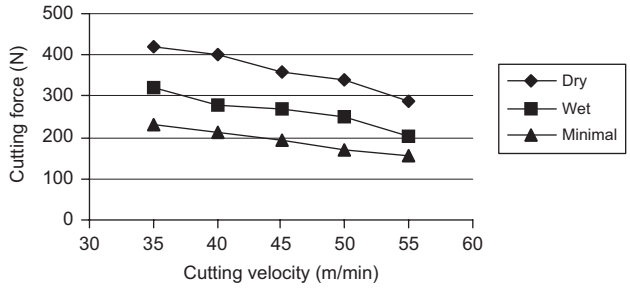


Fig. 12. Comparison of cutting force in wet, dry and minimal conditions for T1 [51].

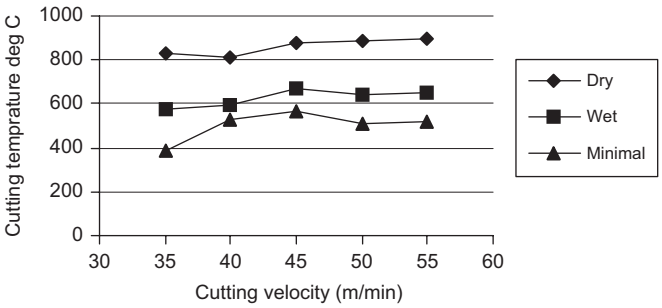


Fig. 13. Comparison of cutting temperature for dry, wet and minimal conditions for T1 [51].

cutting fluid to the underside of the chip, facilitating its passage to the tool–chip interface resulting in the reduction of friction.

The cutting temperature observed in minimum fluid application is comparatively less than that in dry and wet turning as shown in Fig. 13 for both the tools because during the minimum fluid application, cooling occurs by convective as well as evaporative heat transfer. During minimal application, fluid droplets with their high velocity can puncture the blanket of vapors formed and reach the hot tool interfaces facilitating evaporative heat transfer, which is more efficient than the convective heat transfer. Cutting fluid injection thus provides better lubrication and effective heat transfer leading to low cutting temperature than that possible during conventional wet turning. The influence of operating parameters in minimal fluid application was evaluated and it was observed that the cutting performance mainly depends on fluid application parameters such as nozzle pressure, number of pulses and amount of cutting fluid in each pulse. So it is finally concluded that by carefully choosing these parameters it is possible to produce high quality components with minimum fluid application [51].

It is found that during minimal fluid application, the cutting fluid can penetrate and firmly adhere to the work surface resulting in the promotion of plastic flow on the backside of the chip due to Rebinder effect. This relieves a part of the compressive stress and promotes chip curl that reduces tool–chip contact length. In the present investigation, tool–chip contact length was the least during minimal application followed by wet turning and dry turning over the entire cutting range. The cutting tool temperature was lower in case of minimal fluid application condition as cooling occurs due to both convective and evaporative heat transfer. Further cutting force is lower with minimal fluid application as compared to dry and conventional wet turning [52].

Turning of thoroughly hardened AISI 52100 steel with coated CBN inserts under minimum volume of oil (MVO), dry cutting and wet cutting (flood of soluble oil), has been studied. Dry cutting presented the smallest surface roughness and minimum tool wear out of these three cooling approaches. In dry cutting, the cutting

zone temperature increases, this increase in temperature makes the deformation and shearing of the chip easier and does not harm the tool much, since the tool is quite resistant to high temperature. When compressed air and MVO were used, coolants did not allow the temperature to increase too much. Therefore, the tool was under the high pressure caused by the high hardness of the chip and workpiece material, which caused the increase in tool wear and surface roughness. Wet condition presented the highest roughness, due to an opposite cause: the temperature was very low due to the cooling effect of the cutting fluid, which made the forces and vibration to increase [53].

Author investigated the effects of oil–water combined mist on turning stainless steel with the use of 17 ml/h oil and 150 ml/h water mixture. The use of oil–water combined mist could prevent the production of built-up-edge (BUE) while BUE was observed when cutting dry or oil mist. BUE is an important factor for workpiece surface roughness. Thus the workpiece surface finish under oil–water combined mist was better than that under dry, oil mist or water-soluble oil applications. Lower cutting temperatures were also observed with the use of oil–water combined mist compared to cutting dry or with oil mist [54].

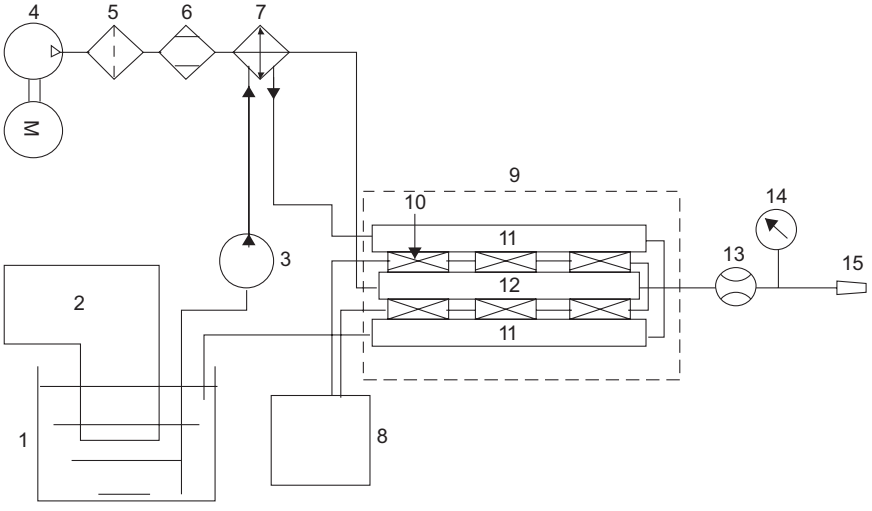
During finish turning of Inconel-718 under the effect of minimal quantity lubrication, cooling air, and cooling air and minimal quantity lubrication (CAMQL), result reveals that application of cooling air and CAMQL resulted in drastic reduction in tool wear and surface roughness, and significant improvement in chip shape. There is 78% and 124% improvement in tool life with cooling air and CAMQL, respectively. Compared with liquids, gases have relatively poor cooling ability due to their low specific heat and heat conductivity. However, poor cooling ability of compressed gas can be improved by refrigerating it to generate a greater temperature difference between the cutting zone and the incoming gas. In the cooling air cutting of difficult-to-cut materials, cooling air was jetted to the cutting zone at a high pressure and dissipated the heat produced by the cutting process by means of convection. For CAMQL, the addition of a very small amount of cutting oil in cooling air stream further reduced the cutting temperature by reducing the friction at the cutting interface. Besides this, the evaporation of cutting oil also decreased the cutting temperature. Therefore, the best tool life is obtained with CAMQL. Further it is observed that smallest surface roughness values are obtained with CAMQL, followed by the application of cooling air and dry cutting, this is due to reduction in tool nose wear under cooling/lubrication conditions. In this author developed a composite refrigeration method, which combines semiconductor refrigeration with vapor compression refrigeration as mentioned in Fig. 14. Result reveals that this equipment has lot of advantages such as high refrigeration speed and response speed, and excellent control capability upon the temperature of cooling gas [55].

MQL of air–oil mixture is fed under 0.276 Mpa (40 psi) pressure through a 0.762-mm (0.03-in) diameter opening in the tool holder. It is found that the application of MQL can effectively reduce the tangential cutting force. With the use of MQL this force reduces by 24.4% of that during dry cutting and 32.2% of that during flood conditions, especially at low cutting speeds. The MQL shows a strong influence on the cutting temperature over a wide range of speeds, and it also lends itself to a lower cutting tool wear rate as compared to completely dry machining. However, as compared to flood cooling, MQL is expected to generate more cutting fluid aerosol due to the splash mechanism associated with mist application [56].

Three types of nozzles are used in MQL turning of Inconel-718, an ordinary type and cover types for normal and oblique spraying of oil mist. Cover-type nozzles are specially designed and used for concentrating small amounts of oil mist to the cutting point and increasing the effectiveness of MQL. Result reveals that when cutting oil is supplied at 15 ml/h, in MQL machining with the ordinary-type nozzle, tool life is 3459 m in cutting length and 44 min in cutting time, which is reasonably good. The cover-type nozzle for normal spraying provided longer tool lives than the ordinary nozzle for the same oil consumption. Further the cover-type nozzle for oblique spraying exhibited better performance than that for normal spraying. It is concluded that control of oil mist flow and shortening of the distance from the nozzle to the tool tip are quite effective for enhancing the cutting performance of MQL machining especially for micro-litre range [57].

3.1. Performance of MQL/NDM under different cutting regime

1. During the turning with coated tools under MQL, optimization of air pressure is needed if oxygen is used as carrier gas for applying MQL to finish turning, because by increasing the air



Where (1) water container, (2) vapor compression refrigeration system, (3) water pump, (4)compressor, (5) filter, (6) drier, (7) heat exchanger, (8) control box, (9) semiconductor refrigeration system, (10) thermopile,(11) heat absorber,(12) cooler, (13) flow meter, (14) pressure gauge, (15) nozzle.

Fig. 14. Schematic sketch of new cooling gas equipment [55].

pressure the oxidation of coating is accelerated by abundant oxygen.
2. The cooling efficiency depends on the specific heat of coolant gas. A coolant of higher specific heat can receive more heat from the tool and workpiece. Thus air acts as a better carrier gas in comparison to argon.
3. With MQL technique, a remarkable reduction of machining costs can be obtained because the quantity of lubricant used is small.
4. Lubricating the rake surface of a tip by the MQL technique does not produce evident wear reduction. Lubricating the flank surface of a tip by the MQL technique reduces the tool wear and increases the tool life.
5. In MQL, vegetable oil, ester oil, or equivalent synthetic fluids are preferred because of their superior lubrication and better performance at high pressure. If these fluids are properly selected in relation to their carrier gas, they may result in less cost per cut than the combined cost of fluid, fluid disposal and a continuous fluid management system in the traditional cutting fluid applications.

4. Role of high-pressure coolant

High-pressure coolant delivery is an emerging technology that delivers a high-pressure fluid to the tool and machined material. The high fluid pressure allows a better penetration of the fluid into the tool–workpiece and tool–chip contact regions as shown in Fig. 15, thus providing a better cooling effect and decrease in tool wear through lubrication of the contact areas [58,59]. The high-pressure coolant jet creates a hydraulic wedge between the tool and workpiece, penetrating the interface with a speed exceeding that required even for high-speed machining and also alters the chip flow conditions [45]. Coolant supply at high pressure tends to lift the chip after passing through the deformation zone resulting in reduction in the tool–chip contact length/area [60].

The performance of CBN, binder-less CBN (BCBN) and PCD tools for high-speed machining of Ti–6Al–4V alloys with high-pressure coolant is evaluated. Results revel that high-pressure coolant produces better lubrication and more efficient cooling at the chip–tool interface. The cooling effect eliminates the welding of the tool and chip or the built-up edges and improves the tool life, as well as the surface finish. BCBN tools are free from the binder element cobalt that readily reacts with titanium. Chips produced by BCBN tools show no diffusion of the tool materials. This results in longer tool life of BCBN tools in comparison to CBN and PCD. Since the BCBN tools show significantly improved tool life, better surface finish, and lower cutting forces, it can be concluded that BCBN tools are more suitable cutting tool materials for machining titanium alloys [6].

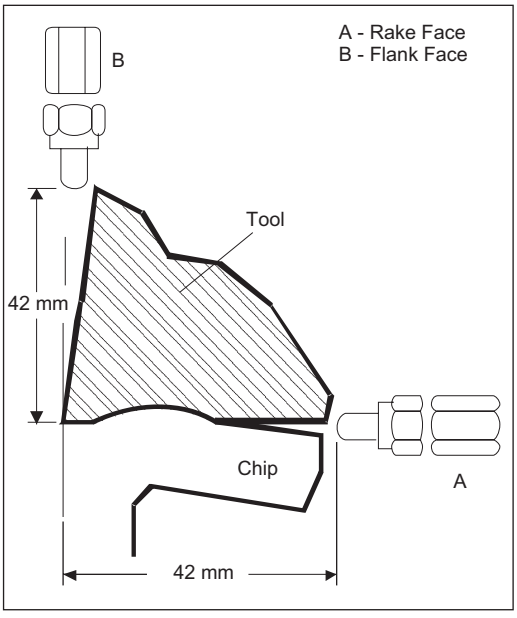


Fig. 15. Position of cutting fluid hoses [59].

During the cutting trials using high-pressure coolant delivery devices, it is found that the coolant not only offers more efficient cooling characteristics and improves tool wear but also results in reduced contact lengths as the coolant delivery pressure forces the chip away from the tool rake face [61,62].

Cubic boron nitride and ceramic cutting tools are not recommended for high-speed machining of titanium alloys with high-pressure coolant supply as they tend to suffer excessive nose wear and severe chipping and/or fracture of the cutting edge [63].

In finish turning of AISI 1045 steel using coated carbide tools under high-pressure fluid (with high and low flow rate), dry cutting and conventional fluid application (low pressure, high flow rate, no specific direction) the tool wear was studied. For HPC three directions of high-pressure fluid were used: (a) towards the chip–tool interface (tool rake face), (b) towards the workpiece–tool interface (flank face) and (c) towards both flank and rake face. As shown in Fig. 16 the longest tool lives were obtained when fluid was applied either simultaneously on the rake and flank faces with high pressure and high flow rate, or solely on the flank face with high pressure and low flow rate. When fluid was injected on the rake face, the adhesion between chip and tool was strong, causing the removal of tool particles. When the adhered chip material was removed from the tool by the chip flow, it resulted in a large crater wear. Fact is that the fluid was not able to penetrate between chip and tool to perform lubrication, since no fluid elements were found on the crater wear region in the EDS analysis [59].

Tool life generally increases with increase in coolant supply pressure. This can be attributed to the ability of the high-pressure coolant to lift the chip and gain access closer to the cutting interface. This action leads to a reduction of the seizure region, thus lowering the friction coefficient, which in turn results in reduction in cutting temperature and cutting forces. Compared to conventional coolant supplies, tool life improved as much as 740%, while machining at 203 bar coolant pressure at a speed of 50 m/min. Chip segmentation depends upon the cutting conditions employed and further to a greater extent on the coolant pressure [64]. Lower cutting forces were generated while machining Inconel-718 with whisker reinforced ceramic tool, at higher coolant supply pressure due to improved cooling and lubrication at the cutting interface. This improvement may be due to chip segmentation caused by the high-pressure coolant jet. Tool life decreased with 20.3 MPa coolant supply pressure due to accelerated notching of the tool [65].

The surface roughness value also varies steadily with prolonged machining under high coolant supply pressure. This can be attributed to the gradual tool wear caused by the significant reduction in temperature at the cutting interface. This helps to maintain the geometry of the tool cutting edge for longer periods. The surface roughness values recorded in all the cutting conditions investigated are generally well below the stipulated rejection criterion of 1.6 μm. This shows that the finish of the machined surface is not affected while machining Ti–6Al–4V alloy with high coolant pressures, not withstanding the possibility of water-jet abrasion of the machined surface during the machining process. There is no evidence of subsurface defects such as cracks, laps, visible tears or shear deformation after machining Ti–6Al–4V

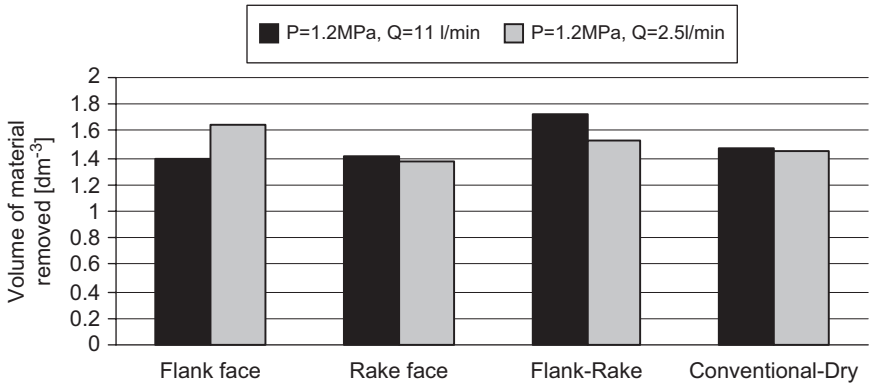


Fig. 16. Volume of material removed per tool life under different conditions [59].

alloy with both conventional and high-pressure coolant supplies. With HPC supply, there is lesser hardening effect as well as microstructural damage on the machined surface due to efficient coolant supply conditions and increased access of the coolant to the chip–tool interface. It contributes to reducing friction coefficient and the resistance to primary shear stress. There is less of heat generation and hence the lower temperature and plastic flow during machining. On the other hand, there is a hardening of machined surface after machining with conventional coolant flow due to irregular cooling effect that promotes rapid quenching effect [63].

Turning of titanium under high-pressure jet results in reduction of cutting forces, the tool tip temperature falls to such a degree that the cutting edge of the insert does not break or suffer plastic deformation, and fails only from continuous wear. Machining time is reduced by 50% and chip flow is doubled. With high pressure, there is virtually no adhesion between the tool and the workpiece material, so that the tool cuts better. This improvement is apparent in the surface finish. Further it is concluded that it is effective to use a high-pressure water-jet system (pressure of 11 MPa and flow rate of 11 l/min) in the turning of titanium [66].

Higher thermal conductivity, higher momentum and enhanced convective heat transfer coefficient of water-soluble oil in high pressure supply while turning Ti–6Al–4V lead to better cooling and more chip curling with smaller broken chips. Chip breakability under water-soluble oil is better in comparison to neat oil. Further there is significant reduction in chip–tool contact length with neat oil as well as water-soluble oil. This is attributed to the lifting of the chip leading to chip curling under the action of the high-pressure coolant jet. High-pressure neat oil significantly provides beneficial effect on tool life over conventional wet environment. But most importantly high-pressure water-soluble oil provides drastic improvement on tool life throughout the experiment. The cutting force reduces significantly under high-pressure cooling environment. The main cutting force and the specific energy are minimum under high-pressure neat oil and the resultant feed force and the thrust force is minimum under high-pressure water-soluble oil [67].

Surface finish and tool life both improve with CBN machining under HPC. As in HPC coolant is able to penetrate deep into the chip–tool interface, thus reduces diffusion–dissolution wear, which is a dominant tool wear mechanism with CBN cutting [68].

4.1. Performance of HPC under different cutting regime

1. Tool life increases with increasing coolant pressure supply; once a critical value of pressure has been reached any further increase in coolant pressure will only result in marginal increase in tool life.
2. During machining of aerospace alloys at high coolant pressure, well-segmented C-shaped chips are generated. Thus it is clear that chip segmentation depends to a great extent on the coolant pressure employed.
3. Low cutting forces are generated due to improved cooling and lubrication with HPC. Surface finish is optimum and surface is free from physical damages such as tears, laps or cracks in almost all the cutting conditions with HPC during turning of titanium alloy.
4. During turning of hard metals with CBN tools, low CBN content tools give better performance under HPC in terms of tool life with reduced notch wear.
5. With HPC supply, lesser hardening effect as well as microstructural damage was observed on the machined surface due to efficient coolant supply conditions and increased access of the coolant to the chip–tool interface.
6. HPC supply shortens the length of contact on the rake face of the tool and thus greatly reduces cutting and feed forces.

5. Cutting mechanics with solid coolants/lubricants

The application of conventional cutting fluids creates some techno-environmental problems, such as environmental pollution, biological problems to operators, water pollution, etc. [69]. Further, the cutting fluids also incur a major portion of the total manufacturing cost [70]. All these factors prompt investigations on the use of biodegradable cutting fluids or the elimination of the use of cutting fluids. However, any attempt to minimize or avoid the coolant can be dealt with only by replacing the functions normally met by the coolants with some other means.

Machining with solid lubricants is one attempt to avoid the use of cutting fluids [71].

Graphite and molybdenum disulphide (MoS_2) are the predominant materials used as solid lubricant [72]. In the form of dry powder these materials are effective lubricant additives due to their lamellar structure. The lamellas orient parallel to the surface in the direction of motion. Even between highly loaded stationary surfaces, the lamellar structure is able to prevent contact. In the direction of motion lamellas easily shear over each other resulting in a low friction. Large particles perform better on relatively rough surface at low speed, finer particle on relatively smooth surface and at higher speeds. Other components that are useful solid lubricants include boron nitride, polytetrafluorethylene (PTFE), talc, calcium fluoride, cerium fluoride and tungsten disulphides.

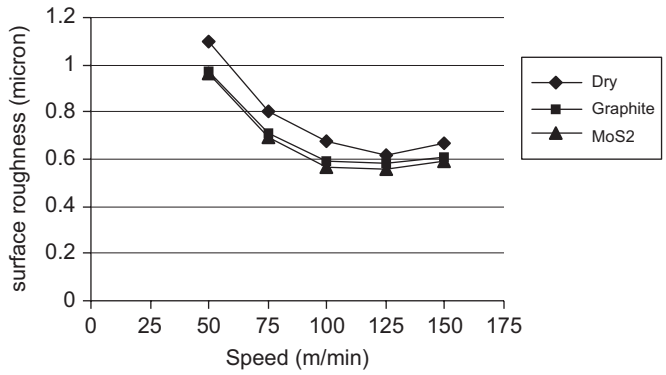


Fig. 17. Variation of surface roughness with cutting speed at $f = 0.12$ mm/rev, effective rake angle (α) = 26°, nose radius (r) = 1.2 mm [73].

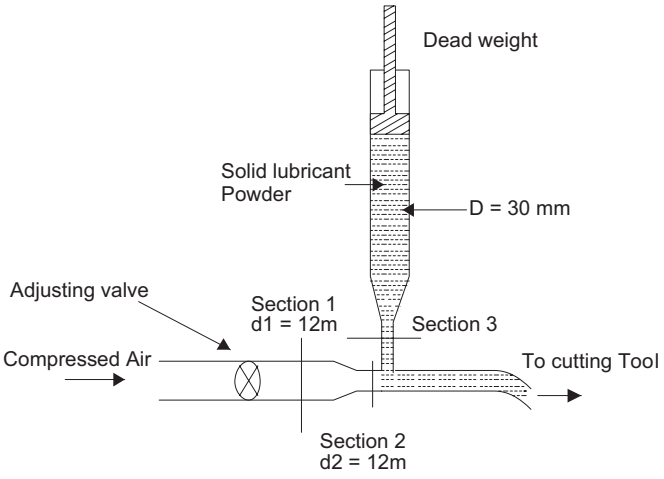


Fig. 18. Powder flow arrangement through T-Injection pipe [75].

During the machining of thoroughly hardened AISI 52100 steel with ceramic inserts by using solid lubricants like graphite and molybdenum disulphide, it was observed that at high cutting speed range, the solid lubricants were more effective. As indicated in Fig. 17, surface roughness was found to be decreasing with the increase of the cutting speed up to 125 m/min and after that it started increasing at high cutting speeds. This could be due to the reduction in the cutting forces at high speed. The high value of surface roughness above 125 m/min could be due to the wear of the cutting tools associated at higher speeds. Solid lubricant assisted hard turning produced low value of surface roughness as compared to the dry hard turning. The decrease in surface roughness due to solid lubricants can be attributed to the inherent lubricating properties of the solid lubricants even at extreme temperatures. This is due to the layered lattice structure of these lubricants. As indicated in Fig. 17 there is a decrease in surface roughness value by 8%–10% due to graphite and by 13%–15% due to molybdenum disulphide. The lower values of surface roughness produced by molybdenum disulphide can be attributed to its strong adhesion as compared to graphite [73].

During the turning of EN8 steel workpiece with cemented carbide tool in the presence of solid lubricants (a mixture of graphite and boric acid with SAE 40 oil), cutting forces were measured to assess the lubricating properties of solid lubricants. The lubricant effectiveness in minimizing the frictional effects at the tool and workpiece interaction, in case of solid lubricant assisted machining, is evident from the reduced cutting forces compared to dry and wet machining. This performance of solid lubricants is due to its lattice layer structure that allows it to act as an effective solid lubricant film.

It is observed that rate of flank wear is less with solid lubricant assisted machining compared to wet and dry machining. The solid lubricant mixture creates a thin lubricating film on the workpiece and causes reduction of flank wear. Low coefficient of friction, sliding action and low shear resistance within the contact interface are the reasons for reduction of flank wear with solid lubricants. Among the lubricants, 20% boric acid in SAE 40 oil provided better performance for the selected tool-work combination and cutting conditions. But not much change was observed beyond 20%. This can be attributed to the fact that high viscosity of the solid lubricant decreases their sliding nature [74].

Solid lubricant is supplied with assistance of air as mentioned in Fig. 18. During the turning due to high work–tool interface temperature, the solid lubricant melts and smears, creating a thin lubricating film on the rake face of the tool. The substantial reduction in flank wear is observed due to the low coefficient of friction and sliding action. Particles of varying size of graphite and boric acid are employed and it is observed that the 50 μm particle size of boric acid improves the process performance by reducing cutting forces and tool flank wear [75].

Solid lubricant assisted machining is a novel concept to control the machining zone temperature without polluting the environment. Experiments were carried out to study the effect of solid lubricants on surface finish and chip thickness. It was observed that both the factors improved by the use of solid lubricants because of effective removal of heat from the cutting zone [76].

5.1. Performance of solid coolant/lubricant under different cutting regime

1. Low values of surface roughness while turning with solid lubricants is due to the inherent lubricating properties of these lubricants even at extreme temperatures. Value of surface roughness produced by molybdenum disulphide as lubricant is lower than that produced by graphite as lubricant due to its strong adhesion quality in comparison to graphite.
2. The value of cutting forces is less with solid lubricants as compared to dry and wet machining due to the lattice layer structure of solid lubricants, which acts as an effective lubricant film.
3. Above all, these lubricants are environment-friendly and produce no harmful effect on the newly generated work surface.

6. Role of air/vapor/gas as coolant

Green cutting has become focus of attention in ecological and environmental protection. Water vapor and air are cheap, pollution-free and eco-friendly alternatives in cooling. Therefore these are good and economical coolant and lubricant. In the 1990s, Podgorkv proposed a new and pollution-free green cutting technique with water vapor as coolant and lubricant during cutting process [77].

The nitrogen gas, liquid nitrogen and compressed air were delivered under pressure and directed into the tool–chip interface via a bespoke nozzle sited on the tool holder.

This method gives the best operating conditions to assist the metal cutting operation [2]. Current industrial advice from tool manufacturers is to use compressed air as a cutting fluid during high-speed cutting operations. However, it is still not clear whether this environment assists the cutting process or if its popularity is due to the convenient availability of compressed air

in the workshop and its ability to remove cutting chips from the work zone [78]. The application of gases (nitrogen, oxygen and carbon dioxide) produced lower cutting force compared to dry and wet cutting. The value of surface roughness was nearly equal in all the cases. Gas application in turning provided higher shear angle value than that in dry and wet cutting [79]. While using oxygen gas instead of cutting fluid, experimental study concluded that the application of oxygen improved surface quality and reduced cutting forces. It was observed that gas pressure also influenced as a chip breaker [80].

An air-cooling system with air-vortex flow arrangement was designed for reducing the heat generated at the tool–chip interface during the turning of heat-treated (SAE 52100) bearing steel. In this, air is initially ejected towards the cutting region at 0 °C as indicated in Fig. 19 tool wear is less as compared to that in dry cutting. However, the performance is not superior to that of flood cooling in terms of tool wear. Because air-cooling alone has not provided a lubrication effect. Further an air–oil-cooling system is used where an oil coolant is supplied through the cooling nozzle. Thus in this way mist coolant is supplied to the cutting area at a temperature of 0 °C, providing cooling and lubrication effects simultaneously. By changing to air–oil cooling, tool chipping is eliminated and tool wear is reduced by over 13% relative to air-jet cooling. This performance is even better than flood cooling [81].

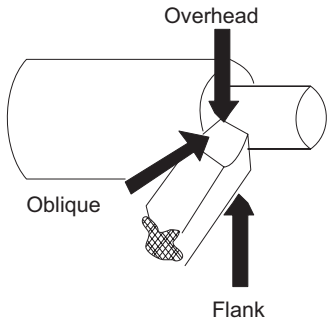


Fig. 19. Ejection direction of the coolant [81].

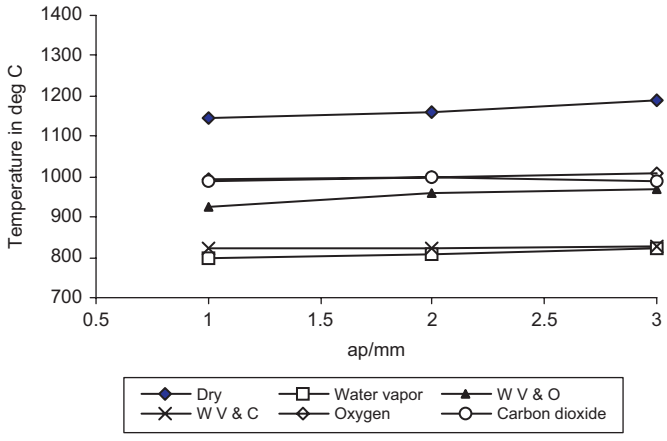


Fig. 20. Temperature variation with depth of cut under different fluid applications [82].

During the turning of ANSI 1045 steel with cemented carbide tools in the presence of water vapor, carbon dioxide gas, oxygen gas and mixture of vapor and gas as cooling medium, it was found that as compared to dry cutting and wet cutting, F_c (cutting force) reduced by 20–40% and 10–15%, respectively, with application of water vapor, gas and mixture of vapor and gas as lubricant. As water vapor form high velocity jet flow by nozzle, water vapors fill up capillaries in cutting zone and form boundary lubricating layer. Thus water vapors alleviate the friction and result in reduced contact length of tool–chip, so that the tool flank wear is alleviated. When water vapors were used as coolant and lubricant, the cutting temperature was lower (<800 °C at cutting speed $V_c = 117.6$ m/min) than that under other lubrication conditions as shown in Fig. 20.

So it reveals that water vapor can alleviate diffusion and adhesion type of tool wear due to low temperature at the cutting zone. With the application of water vapor at high cutting speed, the tool life increases two times that with dry cutting. Thus the benefits of water vapors as coolant are clear. It is cheap and pollution-free [82].

As mentioned in Fig. 21 the water vapors impinge the tool–chip surface at high velocity and properly fill the tool–chip contact area thus reducing the contact friction and the temperature. It is clear from Fig. 22 that the value of surface roughness is quite low while using water vapor as coolant. Water vapors absolutely penetrate the capillaries of cutting zone. Also an acceptable chip form is produced with water vapors. This makes the basis of green cutting [83].

During the turning of (En32b) plain carbon steel with uncoated turning tools under flood coolant, compressed air blast (20% oxygen at 0.27 MPa), ambient temperature nitrogen gas environment (6% oxygen at 0.27 MPa), cold nitrogen gas (−40 °C start temperature, 0% oxygen at 0.27 MPa), liquid nitrogen gas environment (0.27 MPa, 0% oxygen), and dry cutting conditions, it is revealed that uncoated tools used in nitrogen-cutting environment can provide a 55% reduction in crater wear and 30% reduction in flank wear as compared to that under other environment. The presence of oxygen, in both dry and compressed air ambient temperature environments, has a minimal lubricating effect on continuous cutting applications. From the results it is

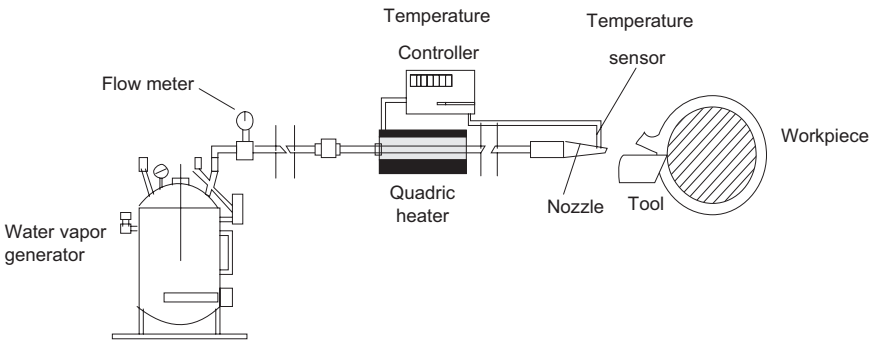


Fig. 21. Schematic sketch of vapor application during turning [83].

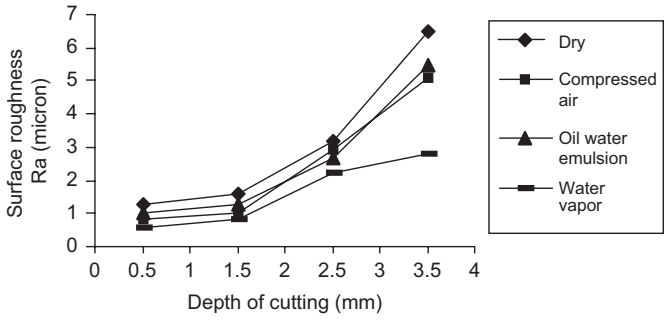
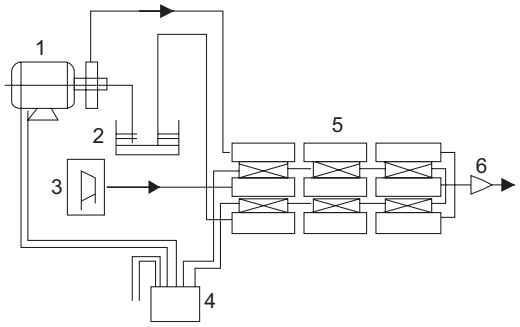


Fig. 22. Variation of surface roughness in presence of different coolants [83].



Where (1) water pump, (2) water container, (3) gas pump,(4) control box, (5) semiconductor refrigeration system, (6) nozzle.

Fig. 23. Schematic sketch of compressed cold nitrogen gas system [87].

clear that nitrogen-cutting fluids assist tool life and should be considered as an alternative to flood coolants while turning (En32b) steel. Nitrogen environment gave the best results because of tighter chip curl and shorter contact lengths compared to the ambient temperature environments [84].

Nozzles of 1.25 mm diameter were used to supply oxygen, carbon dioxide and nitrogen at a pressure of 5 bar to the cutting zone. Turning results reveal that friction coefficient in carbon dioxide was lower than that in oxygen and nitrogen applications. The cooling effect of carbon dioxide is known to be higher than the other two gases. It resulted in lowest cutting force and thrust force in carbon dioxide gas application. It was clear that gas application produced finer surface finish in high feed, although wet machining produced higher surface quality in low feeds. The highest surface roughness was obtained by dry machining [79].

Chilled air, generated by a vortex tube (VT), has been found to be an efficient heat dissipation method in machining. VT can split chilled compressed air into two air streams, one cold and the other hot, with significant temperature difference, yet without using any external energy [85]. During the turning of A390 alloy of aluminum under VT cooling conditions, work material deposit on tool is significantly reduced. For reduction in tool wear the combination of high speed and low feed is the most effective [14].

Author reported that at high cutting speeds, the air-cooling reduces the flank wear but this is not the case at low cutting speeds. In fact, at low cutting speed, for some combination of cutting parameters, the air-cooling slightly increased the flank wear. At low cutting speed, the heat generation is low and tool-job temperature is not as high as in high-speed turning. Therefore, the forced convective heat transfer is not as effective as in high-speed turning. Instead, sometimes in dry turning at low speed, a slight increase of job temperature causes a slight reduction in tool wear due to softening of the material. It indicates that compressed air plays a vital role in reducing the temperature at high-speed turning of grey cast iron with ceramic tool. Further there is very slight reduction in surface roughness in air-cooled cutting in comparison to dry turning up to a speed of 400 m/min. However, at a cutting speed of 480 m/min, where the dry turning provides a very poor surface finish due to rapid tool wear, the air-cooling provided a very good surface finish. In all the cases, air-cooled turning lowered the cutting and feed forces as compared to corresponding forces in dry turning [86].

Machining of Ti–6Al–4V is performed under flood coolant, nitrogen-oil mist, compressed cold nitrogen gas (CCNG) at 0, and 10 °C, and compressed cold nitrogen gas and oil mist (CCNGOM) supply. A new cooling system, which is used to lower the temperature of compressed nitrogen gas is shown in Fig. 23, consisting of water pump, water container, gas pump, control box, semiconductor refrigeration equipment and nozzle. The semiconductor refrigeration equipment includes three semiconductor refrigeration units. Each unit is composed of three heat-removing copper plates and two semiconductor refrigerators. When the semiconductor refrigerator is supplied with direct current, its heat energy may be transferred from one side to another side due to Peltier effect of semiconductor materials. For each semiconductor refrigeration unit, the heat at the hot side of the semiconductor refrigerator will be brought into the surrounding environment by the water stream inside the upper and lower copper plates. Thus, the cold side of the semiconductor refrigerator may remain at extreme low temperature to cool the middle copper plate. Compressed nitrogen gas is cooled by heat exchange with the middle copper plate. After compressed nitrogen gas is cooled continuously along the pipe inside the three semiconductor units, it is jetted to the cutting zone. Result revels that CCNGOM provided the best tool life among all the cooling/lubrication conditions employed. Tool life under CCNGOM is 2.69 times that under dry cutting condition and 1.93 times that with nitrogen–oil-mist, because in CCNGOM small amount of cutting oil performed its lubrication function well under cold nitrogen gas atmosphere and played an important role in reducing tool wear. Further higher tool wear is observed using nitrogen–oil-mist compared to that for CCNG at 10 °C, which indicates that effective cooling of the compressed nitrogen can increases the productivity of the machining process. For the realization of compressed cold nitrogen gas in practical application, its cooling and lubrication capacity needs to be further developed [87].

6.1. Performance of air/vapor/gas as coolant under different cutting regime

1. Air alone did not give satisfactory results but when air–oil mix cooling was used, tool chipping was almost eliminated and tool wear was reduced by over 13% of that in air-jet cooling. The results were even better than those of the flood cooling. In some of the cases particularly at high cutting sped in comparison to dry turning the results of using compressed air are quite encouraging in terms of improvement in surface roughness, reduction in tool wear and cutting forces.
2. The effectiveness of water vapors as coolant was high as compare to that of O_2, Co_2 and mixture of gas, because water vapors form high velocity jet flow by nozzle, thus water vapors fill up capillaries in cutting zone and form boundary lubricating layer. Above all it is green alternative in cooling.
3. Nitrogen environment gave the best result because of tighter chip curl and shorter contact length compared to that of the ambient temperature environment. Compressed cold nitrogen gas and oil mist is the optimal cooling/lubrication condition to improve the tool life, provided proper filtration is used to

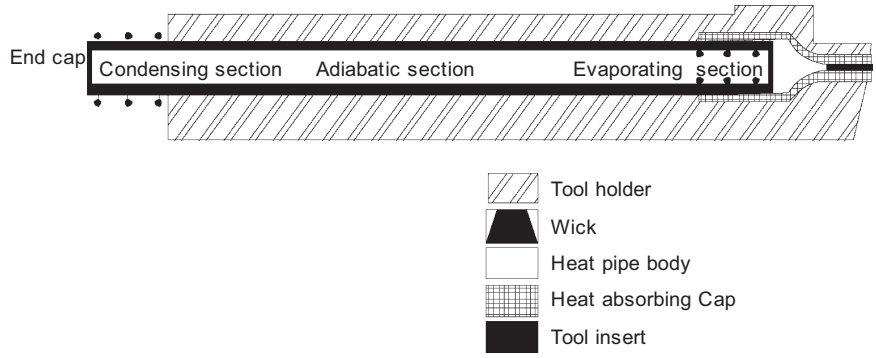


Fig. 24. Schematic sketch of heat pipe [90].

minimize the hazards of oil mist to operator's health.

4. When oxygen, carbon dioxide and nitrogen were applied as coolant, the friction coefficient in carbon dioxide was lower than that with the other two gases.

7. Cutting mechanics with allied cooling processes

During the turning of AISI 304 steel with carbide tools, the effect of three different categories of coolant oils was studied. Results depict that the heat removal at lower cutting speed gives coconut oil a considerable advantage over soluble oil and straight cutting oil. At lower speeds, coconut oil yields lower wear and produces good surface finish compared to that with other cutting fluids [88].

Heat pipes are passive devices with high thermal conductance. They are used to transport heat by means of evaporation and condensation of an appropriate fluid [89]. The heat pipe cooling system is introduced in this investigation. A parametric study was conducted to analyze the effects of different heat pipe parameters such as diameter of heat pipe, length of heat pipe, magnitude of vacuum in the heat pipe and material of heat pipe.

The heat pipe is a hollow closed pipe containing a small amount of water in equilibrium with its own vapors and a wick structure on the inner circumferential area of the pipe maintained at a pressure lower than the atmospheric pressure as shown in Fig. 24. The heat pipe has three sections: evaporating section, adiabatic section and condensing section. The evaporating section receives the external heat from the cutting zone and causes the working fluid (water) to vaporize. The vapors reach the condensing section through the adiabatic section. In the adiabatic section, no heat is absorbed or rejected. The condensing section condenses the vapor and the latent heat of vaporization of the working fluid is rejected into atmosphere. The capillary pressure generated by the meniscus in the wick structure pumps the condensed working fluid back to the evaporating section. The heat transfer continues as long as there is enough heat input in the evaporating section. The heat transfer rate of the heat pipe is much higher than the heat transfer rate of ordinary hollow circular objects of the same specifications. The heat transfer mechanism in the heat pipe is due to the latent heat of vaporization and condensation.

It is clear from Fig. 25 that application of heat pipe reduces flank wear by 5.7% approximately under all conditions. The application of the heat pipe completely eliminates the application of cutting fluids in hard turning with a considerable reduction in tool wear and improvement in surface finish [90]. During the machining of steel using carbide tools with heat pipe cooling system, the author concluded that the heat pipe, embedded with

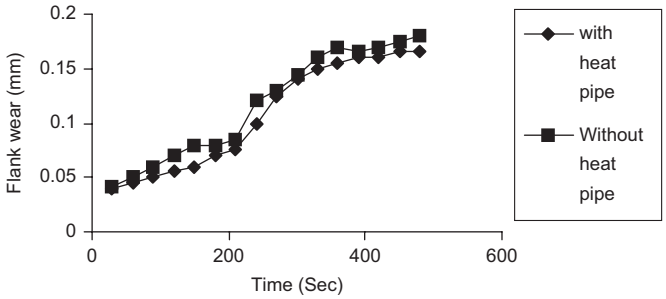


Fig. 25. Comparison of flank wear with heat pipe and without heat pipe [90].

cutting insert, is able to alleviate the cutting tool temperature and thus prolong the tool life [91].

8. Modeling and simulation with cooling techniques

The role of machining process modeling is recognized in industry, due to the relevant advantages that an effective and reliable model can supply [92]. Within this framework the potentialities linked to the use of advanced numerical models and in particular finite element techniques have been recognized by a large number of researchers all over the world [93,94]. For machining under wet cutting conditions, the research till now has been either experimental investigations or finite element method simulations [93]. It is important to characterize the thermal field in the cutting zone in order to design an efficient cryogenic cooling system for high-speed machining [31]. Researchers used Jeager's model of moving heat sources and block partition principles to estimate average temperature at the shear plane and at the chip–tool interface. However, this model could not take into account variation in thermal properties of work and tool material with temperature, the elasto-plastic nature of chip–tool interaction, work–tool interaction at the wear land in flank, etc. [94]. Three-dimensional FEM models are marginally more accurate than two-dimensional models, but these are complex to develop and require more computational effort [95].

A two-dimensional model has been developed for computational evaluation of temperature distribution in turning tools. In this model, the heat developed at the auxiliary flank has been neglected. In machining, heat is generated primarily in three different zones, namely primary shear plane, chip–tool interface and wear land of the principal flank. The mass and heat transport are governed by formation and separation of the chip, speed of the work material and heat conduction and convection. The two-

dimensional section at which the temperature distribution is calculated includes three regions: one is the workpiece moving at the cutting velocity, the second is the chip moving at the bulk chip velocity and the third is the tool which is stationary. The basic equation to be solved for the temperatures of this domain is

$$\rho C_p(T)\left(u\frac{\delta T}{\delta x}+v\frac{\delta T}{\delta y}\right)-K(T)\left(\frac{\delta^2 T}{\delta x^2}+\frac{\delta^2 T}{\delta y^2}\right)=Q' \quad (1)$$

where ρ is the mass density, C_p is the specific heat, k is the thermal conductivity, Q is the internal heat generation rate, u and v represent the velocity components in the x and y directions and T is the temperature. The present analysis uses an integrated approach with a control volume consisting of work, tool and chip. The NISA FEM [FLUID-3D] incompressible software is used for implementing the model with mass flow capability. The average deviation between the estimated and measured temperature throughout the experiments is around 5.4%, which is within the acceptable limit from an engineering viewpoint. The finite element analysis provided distribution of temperature assuming a steady state heat transfer in the workpiece, chip and tool. Expectedly the maximum temperature is found to occur at around the middle of the chip–tool contact length [27].

A two-dimensional thermal model was considered in a cutting process, for calculating temperature distribution in a CBN tool by using the following energy balance equation:

$$\sum \mathrm{qin}+\sum \mathrm{qout}+\sum \mathrm{qgen}=0 \quad (2)$$

where Σqgen is the total rate at which heat is generated in a volume, Σqin is the total rate at which heat enters a volume and Σqout is the total rate at which heat exits a volume. This balance leads to the differential equation similar to that used by Dhar et al. [27]. In the model for calculation of temperature distribution, convection boundary was used along the rake face to represent the cooling effect of LN. Result reveals that for the same heat generation rate with LN cooling, the maximum temperature experienced is only 829 °C as against 1153 °C in dry cutting. Only a small portion of the tool tip experiences a high temperature that ranges from 800 to 600 °C. The isotherm that runs close to the tool tip corresponds to 761 °C. Thus, for the same heat generation rate and tool and workpiece properties, the maximum temperature experienced by the tool decreases by more than 28% for a LN flow rate of 0.25 GPM. However, with the application of liquid nitrogen cooling, the gradient in the tool becomes smaller which is beneficial for the life of the tool [30].

Temperature distribution evaluation was accomplished by using three-dimensional finite element analysis based on the oblique single-edge cutting model, which complies with the Merchant model. The governing equation for this heat transfer analysis is three-dimensional with x, y and z velocity components. The FE predicted tool–chip interface temperature deviated by 23% from measurement of tool–chip temperature by thermocouple for all the cooling conditions tested. In view of the intricacies involved in the heat transfer of the cryogenic cutting process, the FE results can be a good reference for understanding the temperature distribution on tool [96,97]

Based on the finite difference method (FDM), a thermal analysis was performed to decide the ejection direction of the coolant. While cutting with tungsten carbide tool at 170 m/min speed by using FDM analysis, it is revealed that the temperature is higher around rake and clearance faces than in other zones, also the highest temperature region is located on the rake face away from the cutting edge, and it exceeds 600 °C. Hence, we conclude that cooling fluid should be ejected towards the rake and clearance faces, further experiments are conducted under same conditions of coolant flow. In experiments with these cooling conditions, the life of a coated tool is 30% that of the CBN cutting tool [81].

Finite element analysis (FEA) was used to simulate the temperature distribution on the tool, when cutting was performed using heat pipe cooling method. The FEA shows that the temperature values at particular locations without the application of the heat pipe are 748 and 737 °C, respectively, and in the presence of the heat pipe, the temperature values are 715 and 691 °C, respectively. The FEA result shows that temperature drops by 24 °C when the heat pipe is applied. Since the FEA result is more or less the same as that of the experimental result, it is confirmed that the experimental data is significant. However, this FEA simulation shows that the installed heat pipe has a significant effect on the reduction of cutting zone temperature [90]. From the preliminary experiments and FEA, it is clear that the cooling technique helps in removing the heat generated during machining and thus, improves tool life and surface quality [98].

During the turning of Ti–6Al–4V under high-pressure water jet, the finite element simulation, using the updated Lagrangian formulation was used to study the dynamic transient process. It was found that the high-pressure jet increases the amount of residual compression stress in both cutting and feed directions .The presence of compression residual stress leads to a better surface integrity and consequently improves the fatigue property of work material. The result of simulation varies up to 30% of that obtained from experiments. Simulation can be considered a good device for evaluation of residual stress monster after turning [99].

Model was developed to predict the tool flank wear rate and wear progression for near dry turning by considering the effect of cutting conditions, known tool geometry and material properties. The cutting temperature is obtained by considering a moving or stationary heat source in the tool. The coefficients for wear rate model are calibrated by the measured tool wear lengths when turning AISI 1045 steel with uncoated tungsten carbide. The predicted values show good agreement with measured data under near dry turning under different cutting conditions [84].

To address the issue of the environmental concerns of cutting fluids in near dry machining, an analytical model is developed to predict the aerosol generation rate. The cutting fluid aerosol generation in turning process is due to spin-off, splash and evaporation mechanism separately or in combination [100]. In the analytical model, two primary aerosol formation mechanisms are considered: aerosol runaway and evaporation, when air–fluid mixture is applied to the insert flank face. Both the analysis and experimental results show that the aerosol runaway has a significantly higher effect on aerosol generation in near dry turning. The analytical results show a good agreement with the experimental results. The cutting force model is developed by modifying Oxley's model by incorporating lubricating and cooling effects of flood cooling. During the modeling, the cutting temperature is obtained by taking the primary heat source (shear deformation), the secondary heat source (friction) and the heat loss (by flood cooling based on a moving or stationary heat source in the tool) [93].

Using molybdenum disulphide assisted machining, empirical equations have been obtained by response surface methodology to estimate surface roughness with the significant parameters considered for the experimentation, i.e., cutting speed, feed rate, approach angle and rake angle. A first-order mathematical model has been developed and the multiple regression coefficient is found to be 0.5307. This shows that the first-order model can explain the variation in surface roughness to the extent of 53.07%. As the first-order model has low predictability, the second-order model has been developed to see whether it can represent the process better or not.

The second-order surface roughness model thus developed is given below:

$$Y1 = -4.5486 + 1.0856x1 + 1.0706x2 - 1.3629x3 + 0.5378x4 - 0.2376x1^2 + 0.2361x2^2 + 0.0437x3^2 - 0.0888x4^2 \quad (3)$$

where $Y1$ is the estimated response of surface roughness on a logarithmic scale, and $x1$, $x2$, $x3$ and $x4$ are the logarithmic transformations of speed, feed, approach angle and rake angle, respectively. The multiple regression coefficient of the second-order model is found to be 0.9124. On the basis of multiple regression coefficient R^2, it can be concluded that the second-order model is adequate to represent this process [76].

Multiple linear regression models are developed for flank wear and surface roughness using Minitab-15 software. The response variable is the flank wear and the surface roughness, whereas the predictors are cutting speed, feed rate, depth of cut and the viscosity of the cutting fluids. The viscosity of each cutting fluid at 40 °C is considered for the mathematical modeling. Accordingly Eq. (4) and (5) of the fitted model for flank wear and surface roughness are given below:

$$V_b = 0.00052V_c + 0.0194d + 0.336f + 0.000069h - 0.0459 \quad (4)$$

$$R_a = 0.00280V_c + 0.299d + 6.87f + 0.00067\eta + 0.376 \quad (5)$$

where V_b is the flank wear in mm, V_c is the cutting speed in m/min, d is the depth of cut in mm, f is the feed rate in mm/rev, R_a is the surface roughness in μm and η is the viscosity in MPa S. An analysis of variance (ANOVA) is made and it is found that feed rate has greater influence on surface roughness (61.54% contribution) and cutting speed has greater influence on tool wear (46.49% contribution). Further it is found that cutting fluid has considerable influence on both surface roughness and tool wear. Effectiveness of the cutting fluids in reducing the tool wear and improving the surface finish is found by comparing the performance. In general, coconut oil is found to be a better cutting fluid than the conventional mineral oils in reducing the tool wear and surface roughness [88].

Author proposed tool wear model based on the abrasive mechanism, the adhesive mechanism, and the diffusive mechanism. The important factors related to this model are contact stresses and temperatures in MQL that are obtained from the cutting force and temperature models. Using the volumetric loss, due to different wear mechanisms, to the tool insert geometry is developed the flank face wear model. According to the geometry of the tool insert used in this study, the flank wear rate is given by

$$\frac{dL_{VB}}{dt} = \cot\gamma - \frac{\tan\alpha}{L_{VB}}\left\{\begin{array}{c} 3.697\times10^{-7}(1/H_t)V_C L_{VB}\sigma + 3.6761\times10^{-16}e^{7.456\times10^{-4}T}V_C\sigma \\ +1.29\times10^{5}\sqrt{V_C}L_{VB}e^{-20570/T+273} \end{array}\right\} \quad (6)$$

Further the tool flank wear model is confirmed by comparing the predicted values with the measured values and it is found that there is a good agreement between predicted and measured values. Apart from the flank wear model, cutting temperature model, cutting force model and aerosol generation rate model are also developed [56].

A finite element (FE) 3-D model (using ANSYS 6.1) is developed for the simulation of temperature generated at the tool–chip interface. The temperature is estimated by considering machining heat flux over the tool–chip contact area on a tool insert of a cutting tool with and without use of heat pipe. To achieve more realistic and accurate simulation results, the model takes into account the real geometry of the cutting tool and the thermal resistance. A typical simulation for a cutting tool without a heat pipe for heat flow $Q = 15.7$ W shows that the maximum temperature near the heat source is 352 °C. With the same heat flow the maximum tool tip temperature is reduced to 293 °C with a heat pipe installed in the cutting tool. It may be inferred that the heat pipe system designed has lower thermal resistance than the non-heat pipe system. Without a heat pipe, the heat transferred to the tool is resisted and it accumulates on the tool–chip interface, and takes time to diffuse into the inner region of the cutting tool. Further it is inferred that the heat generated in machining can be effectively removed by the use of a heat pipe installed on a cutting tool insert. The experimental results also agree with the FEM analysis in the sense that the installed heat pipe in a cutting tool has a significant effect on the temperature drop at the tool–chip interface, tool wear reduction and tool life prolongation in machining [101].

During turning of AISI P20 steel under the effect of cryogenic cooling, a model is developed using face-centered central composite design. The responses (cutting force, surface roughness, tool life and power consumption) are consequently expressed in form of regression equations. To determine the optimum values of cutting parameters, single response and multi-response optimization using desirability function is practiced, results reveal that highest desirability could be obtained at low level of cutting speed, feed, depth of cut and high nose radius. Further the variation between experimental and predicted data is studied which is in between −6.25% and 2.6%, it validates the results drawn from desirability plots [102].

A new tool wear/tool life relationship has been developed for NDM with coated grooved tools, by extending the Taylor-type equation to include mist-spray delivery parameters by modifying the tool coating effect factor as shown by

$$T = T_R\frac{km}{f^{n1}d^{n2}}\left(\frac{V_R}{V}\right)^{(1/nc)(1/N_{NDM})} \quad (7)$$

where N_{NDM} is the NDM effect factor.

More accurate and consistent estimates of tool wear are made by using the new predictive model for NDM compared to dry machining models. The G mapping function allows the users of the empirical based model to customize the equation to consider a wide variety of mist-spray delivery parameters, including nozzle position, metal working fluids (MWF) volumetric flow rate and MWF type [103].

9. Conclusions and future work

1. The application of cryogenic cooling for turning of difficult-to-cut materials has resulted in several fold increase in tool life without compromising on the environmental conditions. Tool life improves dramatically due to the fact that cryogenic fluid is able to penetrate the chip–tool interface and perform both lubrication and cooling functions satisfactorily but cooling function in particular. Productivity is also high as cryogenic cooling shows better results at higher feed rates.
2. With the MQL/NDM technique, there can be a remarkable reduction in machining cost, quantity of lubricant used and surface roughness by properly orienting the nozzle on flank face of the tool. Further performance of MQL can be enhanced using chip evacuation system. From viewpoint of cost, health, safety and environment, performance of MQL technique is better with the use of vegetable oils as compared to mineral oils.
3. Turning with HPC technique results in formation of segmented chips, better penetration at interface and thus lower cutting force, better tool life and acceptable surface finish. It seems to be a potential solution for turning of hard-to-cut materials. Directing the nozzle at particular location plays a vital role in machining with HPC.
4. Performance of solid lubricants is better at higher cutting speed, it means they offer opportunities for increasing the

MRR. Higher the adhesion quality of solid lubricants, better will be their performance. Pollution-free environment and capacity to handle high cutting temperature are encouraging the use of these lubricants.

5. Air, water vapor and other environment-friendly gases mixtures are better solutions for green cutting. Air when mixed with oil gives better performance. The use of water vapor as coolant is encouraging due to their better lubrication qualities. Straight oils provide the best lubrication but poor cooling capacities. Water, on the other hand, is an effective cooling agent, removing heat 2.5 times more rapidly than the oil. The performance of water is encouraging when it is mixed with soluble oils.
6. Researchers proposed the use of vegetable oils as coolant in cutting. The performance of coconut oil as coolant was encouraging at lower cutting speeds. It indicates that other types of vegetable oil can also be checked for their suitability as coolant in turning process.
7. The use of heat pipe arrangement in the tool holder is another alternative of low cost environment-friendly cooling in machining.
8. All types of cooling techniques gave good results with almost all the tool materials in particular with carbide (coated/uncoated) and PCBN.
9. Development of analytical models and application of FEA techniques helps in predicting the tool wear, surface characteristics, fluid aerosol generation, etc. under different cooling methods. These models and FEA techniques can serve as a basis for planning machining process with use of different cooling techniques.

9.1. In order to advance the cooling technology in turning, future work on cooling techniques shall emphasize the unresolved issues described below

- An analysis of surface characteristics of the workpiece surface (residual stresses, microstructure, subsurface hardening, etc.) during turning under the influence of different cooling methods, in particular analysis of residual stress and subsurface microstructure while turning with HPC technique.
- Study of the effects of these cooling/lubrication techniques on CBN/PCD tools or tools coated with ceramic, diamond and PCBN based composites and their performance in hard turning applications.
- Investigation of the optimization of flow rate/mixture quality (air and gas mixing) and its impact on tool wear, surface quality and air quality in the atmosphere.
- Study of coolant application direction (rake face, flank face, clearance face, chip backside, etc.) may be individual or simultaneous and their effect on output parameters in turning.
- Development of analytical models based on existing models to predict surface quality, tool wear, workpiece surface characteristics and impact of coolant on shop floor environment.
- Study of the behavior of tool and workpiece under different cooling approaches, with the use of simulation tools.
- Application of these cooling techniques on composites, ceramics and super alloys by selecting different combinations of tool insert geometries (tip radius, grooved tools, effective rake angle, etc.) and further optimization of the turning process.
- To achieve chip breakage and control over chip formation in HPC turning, study of variation in pressure level and flow of the jet is essential.
- Literature clearly indicates that among the various cooling techniques, use of NDM, solid coolants is encouraging in respect of all turning performance parameters along with environmental aspects, so future work in cooling should concentrate on these approaches particularly focusing on optimization of the mixture quality (air and other gases including cryogenic fluids) in NDM and optimization of flow rate as well as particle size during the use of solid lubricants.

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